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Preprint
not peer reviewed

A Novel Approach to Estimating Maximal Lactate Utilization Speed (Fatmax) Using Lactate Measurements

Supplementary materials: none
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Please cite as: D.Varvanets. (2022). A Novel Approach to Estimating Maximal Lactate Utilization Speed (Fatmax) Using Lactate Measurements. *SportRχiv*.

ABSTRACT

Maximizing fat oxidation during exercise, known as Fatmax, is crucial for endurance athletes and metabolic health. Traditional methods for determining Fatmax involve expensive cardiopulmonary exercise testing (CPET) equipment to measure oxygen consumption (VO_2) and carbon dioxide production (VCO_2). This study introduces a cost-effective method to estimate the speed of maximal lactate utilization (Fatmax) using lactate measurements obtained during incremental exercise tests. By leveraging the relationship between lactate dynamics and fat oxidation, we present a mathematical model and a Python implementation to accurately estimate Fatmax from lactate data alone.

INTRODUCTION

During endurance exercise, mitochondria function as the primary source of adenosine triphosphate (ATP). Each time a mitochondrion consumes oxygen, it simultaneously utilizes fuel substrates derived from glucose or fatty acids. Carbohydrate stores—mainly muscle and liver glycogen—are limited compared to fat reserves. Oxidation of palmitate, a common fatty acid, can produce up to 106 molecules of ATP, whereas aerobic glycolysis yields approximately 30 molecules of ATP. Enhancing lipid oxidation pathways is a key mechanism in improving endurance performance, necessitating robust methods to monitor this development effectively.

All authors have read and approved this version of the manuscript.
This article was last modified on October 23, 2022.

In laboratory settings, Fatmax—a biomarker representing the maximal capacity for aerobic lipolysis in an individual[1]—is measured using expensive cardiopulmonary exercise testing (CPET) metabolic carts by analyzing VO2 and VCO2 values[2], which can cost several tens of thousands of dollars. However, this method may reduce the precision of results due to factors such as the impact of CPET equipment on an individual's biomechanics, additional ventilatory resistance, and the imperfect translation of treadmill-based training zones and threshold paces to real-life conditions. Consequently, more practical and cost-effective methods for calculating Fatmax are required.

Lactate testing at specific speed intervals is a common method for monitoring endurance adaptations in athletes. In healthy individuals, baseline blood lactate levels at rest (speed = 0) are typically low, around 0.5 to 2 mmol/L. During exercise within the easy intensity domain, lactate levels remain relatively stable or may slightly decrease due to efficient clearance and utilization. As exercise intensity increases, lactate concentrations begin to rise at a certain threshold. When lactate levels exceed the baseline by approximately 0.5 mmol/L, the aerobic threshold (LT1) is reached, delineating the transition between easy and moderate intensity exercise domains.

With further increases in intensity, the anaerobic threshold (LT2) is reached, beyond which lactate begins to accumulate rapidly because its production outpaces the body's clearance capacity. Intensities above LT2 define the heavy exercise domain, where athletes engage in high-intensity interval training (HIIT)—a critical workout for endurance development in which lactate plays a significant role in exercise-induced adaptations. During rest phases between intervals, lactate levels decrease as it is metabolized by mitochondria and processed through the liver's Cori cycle and the kidneys.

At low exercise intensities, the glycolytic energy system contributes minimally to energy production, resulting in a reduced supply of lactate to the aerobic system. Since aerobic metabolism can utilize additional substrates, this low-intensity condition is characterized by a relative deficiency of lactate or pyruvate. To compensate for this lack of carbohydrate-derived fuel, the body increases the oxidation of fatty acids.

Based on this facts, a mathematical algorithm was created to determine from an exercise interval lactate testing the subject’s fatmax (or lack of pyruvate) speed. A Python code was created by using OpenAi O1 Preview artificial intelligence model.

Mathematical Formula

To estimate Fatmax, we analyze the lactate curve derived from the incremental interval exercise test. LT1 was determined as speed where lactate levels exceed baseline level by 0.5mmon/l. LT2 was determined by using Dmod method. The key steps are:

Mathematical Formula

Let:

- $L(s)$ be the lactate concentration at speed s.
- s_{LT1} be the speed at LT1.
- $s_{\max}$ be the speed at the highest lactate concentration $L_{\max}$.

Dmod Line Equation:

$$L(s) = m \cdot s + b$$

where:

$$m = \frac{L_{\max} - L_{\text{LT1}}}{s_{\max} - s_{\text{LT1}}}$$

$$b = L_{\text{LT1}} - m \cdot s_{\text{LT1}}$$

Perpendicular Distance from Point $(s, L(s))$ to Dmod Line:

$$D(s) = \frac{|A \cdot s + B \cdot L(s) + C|}{\sqrt{A^2 + B^2}}$$

where:

$$A = -m, \quad B = 1, \quad C = -b$$

LT2 Determination:

$$s_{\text{LT2}} = \arg\max_{s \geq s_{\text{LT1}}} D(s)$$

Maximal Lactate Utilization Speed (Fatmax):

- Invert and shift the lactate curve up to LT2:

$$Y_{\text{before LT2}}(s) = -L(s) + L(s_{\text{LT2}})$$

- Fatmax speed s_{Fatmax} is:

$$s_{\text{Fatmax}} = \arg\max_{s \leq s_{\text{LT2}}} Y_{\text{before LT2}}(s)$$

Python code implementation.
The algorithm below asks to enter baseline lactate level, and then interval speeds (km/h) and then corresponding lactate levels (mmol/l).

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.interpolate import PchipInterpolator

# Input data
baseline_lactate = float(input("Enter baseline lactate (mmol/L): "))
speeds_input = input("Enter speed values (km/h), separated by commas: ")
lactate_input = input("Enter lactate values (mmol/L) for the given speeds,
separated by commas: ")

# Convert input strings to numpy arrays
speeds = np.array([float(s.strip()) for s in speeds_input.split(',')])
lactate_values = np.array([float(l.strip()) for l in
lactate_input.split(',')])

# Check that the lengths match
if len(speeds) != len(lactate_values):
    print("Error: The number of speeds and lactate values must be the
same.")
    exit()

# Include baseline data
all_speeds = np.concatenate(([0], speeds))
all_lactate_values = np.concatenate(([baseline_lactate], lactate_values))

# Ensure that the speeds and lactate values are sorted in ascending order
of speed
sorted_indices = np.argsort(all_speeds)
sorted_speeds = all_speeds[sorted_indices]
sorted_lactate_values = all_lactate_values[sorted_indices]

# Use PchipInterpolator for monotonic interpolation
pchip = PchipInterpolator(sorted_speeds, sorted_lactate_values)

# Create a range of speeds for plotting the curve
speed_range = np.linspace(0, speeds[-1] + 1, 500)
lactate_curve = pchip(speed_range)
```

```
# Step 1: Determine LT1

# LT1 is where lactate reaches baseline + 0.5 mmol/L
LT1_threshold = baseline_lactate + 0.5

# Find the maximum speed where lactate is less than baseline lactate
below_baseline_indices = np.where(lactate_curve < baseline_lactate)[0]
if len(below_baseline_indices) > 0:
    min_LT1_speed = speed_range[below_baseline_indices[-1]]
else:
    min_LT1_speed = 0

# Find where lactate_curve crosses LT1 threshold, after min_LT1_speed
indices = np.where((lactate_curve >= LT1_threshold) & (speed_range >=
min_LT1_speed))[0]
if len(indices) > 0:
    LT1_index = indices[0]
    LT1_speed = speed_range[LT1_index]
    LT1_lactate = lactate_curve[LT1_index]
else:
    LT1_speed = None
    print("LT1 not found within the given data range.")

# Step 2: Determine LT2 using Dmod method

if LT1_speed is not None:
    # Coordinates of LT1 point
    x1, y1 = LT1_speed, LT1_lactate
else:
    # If LT1 is not found, use the first point where lactate >= baseline
lactate
    indices = np.where(lactate_curve >= baseline_lactate)[0]
    if len(indices) > 0:
        first_index = indices[0]
        x1, y1 = speed_range[first_index], lactate_curve[first_index]
    else:
        print("Cannot determine LT2 without a valid LT1 point.")
        exit()

# Coordinates of the highest lactate sample point (from user input)
max_lactate_index = np.argmax(lactate_values)
x2 = speeds[max_lactate_index]
```

```
y2 = lactate_values[max_lactate_index]

# Equation of the line between LT1 point and highest lactate sample point
m = (y2 - y1) / (x2 - x1)
b = y1 - m * x1

A = -m
B = 1
C = -b

# Compute distances from the curve to the line, only after LT1
indices_after_LT1 = np.where(speed_range >= x1)[0]
x_values = speed_range[indices_after_LT1]
y_values = lactate_curve[indices_after_LT1]
numerator = np.abs(A * x_values + B * y_values + C)
denominator = np.sqrt(A ** 2 + B ** 2)
distances = numerator / denominator

# Find the point with the maximal distance
LT2_index = np.argmax(distances)
LT2_speed = x_values[LT2_index]
LT2_lactate = y_values[LT2_index]

# Compute foot of perpendicular from LT2 to Dmod line
# Equation of Dmod line: y = m * x + b
# Perpendicular line: y = (-1/m) * x + c_perp
# The foot of the perpendicular (x0, y0) satisfies both equations

# Calculate x0 and y0
m_perp = -1 / m
c_perp = LT2_lactate - m_perp * LT2_speed

# Solve for intersection point (x0, y0)
x0 = (c_perp - b) / (m - m_perp)
y0 = m * x0 + b

# First Graph: Lactate Curve with LT1 and LT2
plt.figure(figsize=(10, 6))
plt.plot(speed_range, lactate_curve, label='Lactate Curve', color='blue')
plt.scatter(speeds, lactate_values, color='green', label='Data Points')

# Plot LT1 and LT2
```

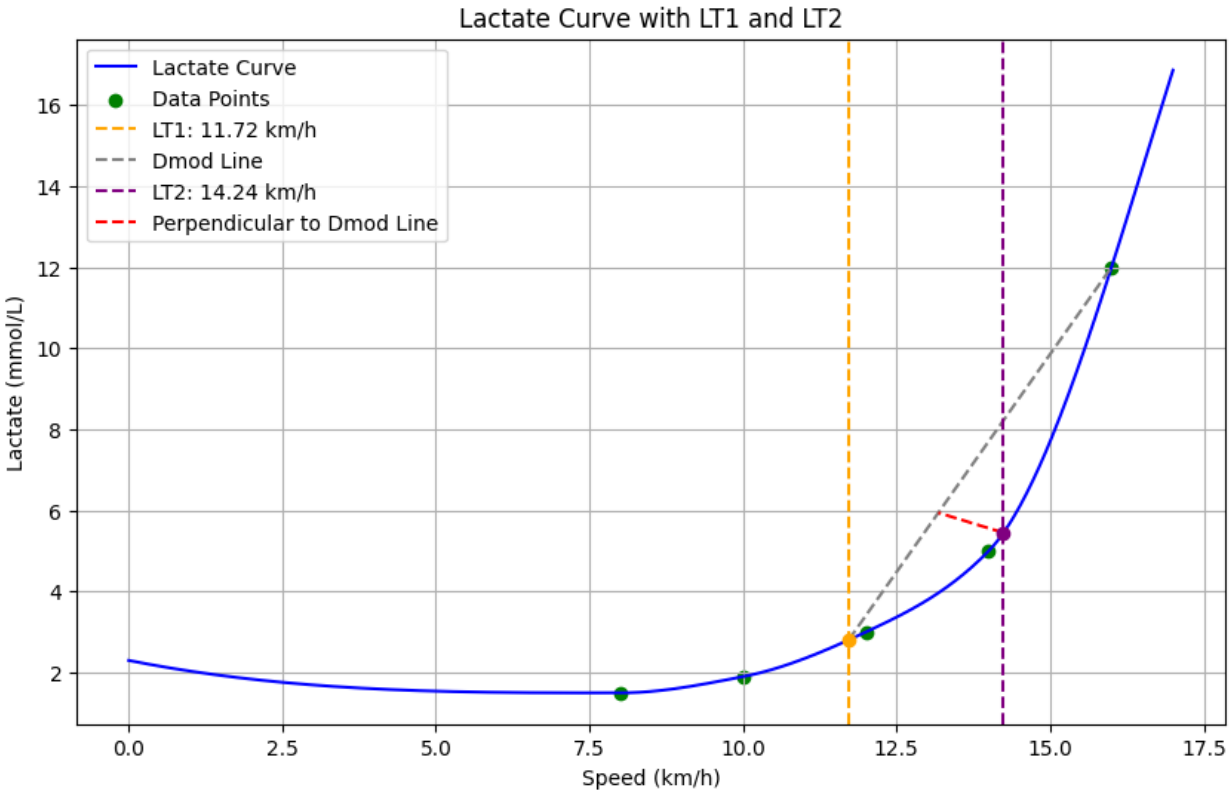
```
if LT1_speed is not None:
    plt.axvline(LT1_speed, color='orange', linestyle='--', label=f'LT1:
{LT1_speed:.2f} km/h')
    plt.scatter(LT1_speed, LT1_lactate, color='orange', zorder=5)
    # Plot the Dmod line
    plt.plot([x1, x2], [y1, y2], color='grey', linestyle='--', label='Dmod
Line')
else:
    print("LT1 could not be determined from the data.")

plt.axvline(LT2_speed, color='purple', linestyle='--', label=f'LT2:
{LT2_speed:.2f} km/h')
plt.scatter(LT2_speed, LT2_lactate, color='purple', zorder=5)

# Plot perpendicular from LT2 to Dmod line
plt.plot([LT2_speed, x0], [LT2_lactate, y0], color='red', linestyle='--',
label='Perpendicular to Dmod Line')

# Labels and legend
plt.title('Lactate Curve with LT1 and LT2')
plt.xlabel('Speed (km/h)')
plt.ylabel('Lactate (mmol/L)')
plt.legend()
plt.grid(True)
plt.show()

# Output LT1 and LT2 values
if LT1_speed is not None:
    print(f"LT1 Speed: {LT1_speed:.2f} km/h, Lactate: {LT1_lactate:.2f}
mmol/L")
else:
    print("LT1 could not be determined from the data.")

print(f"LT2 Speed: {LT2_speed:.2f} km/h, Lactate: {LT2_lactate:.2f}
mmol/L")

# Second Graph: Metabolic Transition Curve
# Lactate value at LT2_speed
lactate_LT2 = LT2_lactate

# Speeds before LT2
indices_before_LT2 = speed_range <= LT2_speed
```

```
speeds_before_LT2 = speed_range[indices_before_LT2]
lactate_before_LT2 = lactate_curve[indices_before_LT2]

# y(x) before LT2
y_before_LT2 = -lactate_before_LT2 + lactate_LT2

# Speeds after LT2
indices_after_LT2 = speed_range >= LT2_speed
speeds_after_LT2 = speed_range[indices_after_LT2]
lactate_after_LT2 = lactate_curve[indices_after_LT2]

# y(x) after LT2
y_after_LT2 = lactate_after_LT2 - lactate_LT2

# Find Max La utilization speed (maximum of y_before_LT2)
max_la_utilization_index = np.argmax(y_before_LT2)
max_la_utilization_speed = speeds_before_LT2[max_la_utilization_index]
max_la_utilization_value = y_before_LT2[max_la_utilization_index]

# Second Graph Plotting
plt.figure(figsize=(10, 6))

# Plot y(x) before LT2
plt.plot(speeds_before_LT2, y_before_LT2, color='darkturquoise',
label='Lack of pyruvate, lipolysis present')

# Plot y(x) after LT2
plt.plot(speeds_after_LT2, y_after_LT2, color='violet', label='Lactate
accumulation, lipolysis absent')

# Mark LT2
plt.axvline(LT2_speed, color='purple', linestyle='--', label=f'LT2:
{LT2_speed:.2f} km/h')

# Mark Max La utilization speed
plt.axvline(max_la_utilization_speed, color='green', linestyle='--',
label=f'Max La utilization speed: {max_la_utilization_speed:.2f} km/h')
plt.scatter(max_la_utilization_speed, max_la_utilization_value,
color='green', zorder=5)

# Labels and legend
plt.title('Metabolic Transition Curve')
```

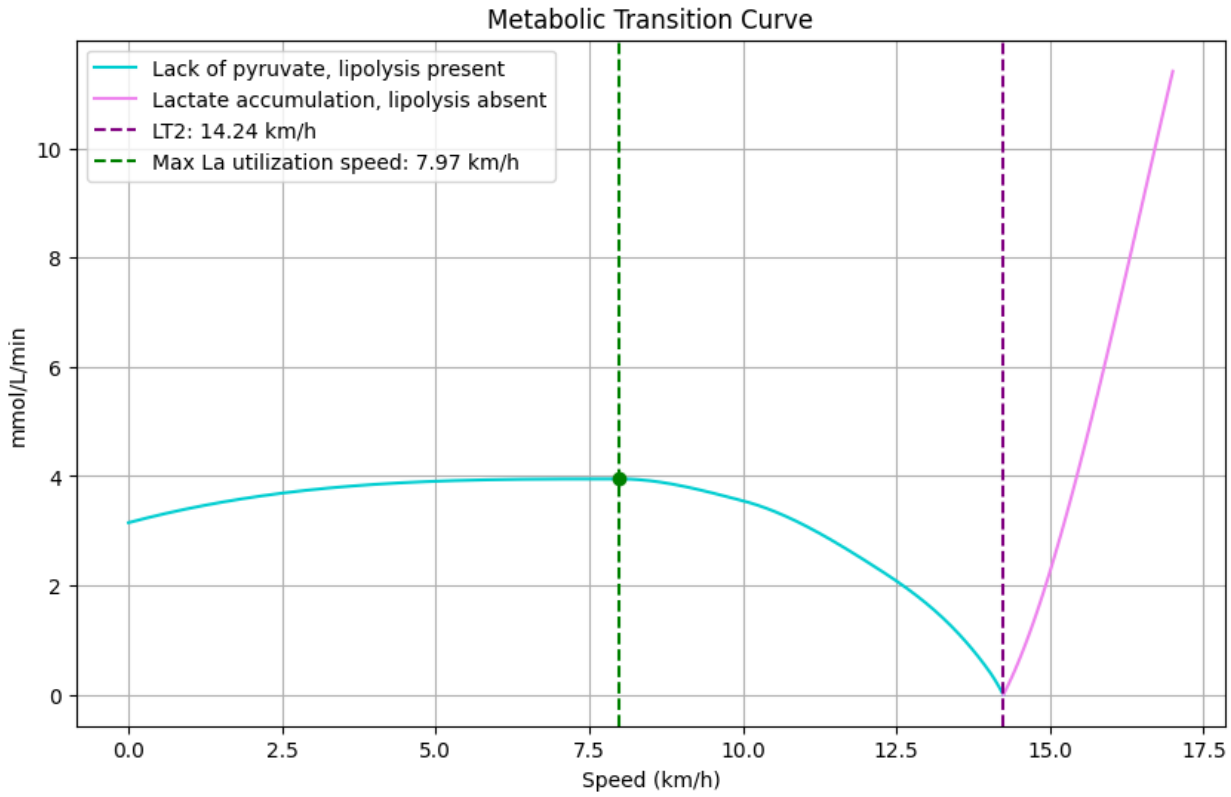
```
plt.xlabel('Speed (km/h)')
plt.ylabel('mmol/L/min')
plt.legend()
plt.grid(True)
plt.show()
```

Results

As an example, baseline lactate value of 2.3mmol/l was entered. The speed at which lactate testing was performed is 8, 10, 12, 14 and 16km/h (4-5min running intervals were used). The corresponding lactate values were: 1.5, 1.9, 3,5, 12mmol/l.
As a result, a lactate curve was drawn where LT1 and LT2 were determined.



The next step is to create based on this input the metabolic transition curve with drawn lines of lack of pyruvate and lactate accumulation by using abovementioned code.



For this subject the Fatmax Speed is 7.79 km/h.

Discussion

This novel method allows for the estimation of Fatmax using lactate measurements obtained during standard incremental exercise tests. By analyzing the lactate curve and applying mathematical modeling, we can determine key metabolic transition points:

LT1: Indicates the onset of lactate accumulation above baseline levels.

LT2: Represents the point of maximal deviation from the linear relationship between LT1 and the highest lactate value.

Maximal Lactate Utilization Speed (Fatmax): The speed at which lactate utilization is maximized, corresponding to peak fat oxidation.

This approach offers a cost-effective alternative to traditional CPET methods, making it accessible for athletes, coaches, and practitioners without access to expensive metabolic equipment.

Conclusion

Estimating Fatmax is essential for optimizing endurance performance and metabolic health. This study presents a practical method to determine the maximal lactate utilization speed using lactate measurements, providing a valuable tool for exercise prescription and monitoring. Future research should

validate this method against gold-standard measures and explore its applicability across different populations.

Contributions

Conception and design of the algorithm: D. Varvanets
Preparation of the manuscript: D. Varvanets

Acknowledgements

None

Funding information

None

Data and Supplementary Material Accessibility

None

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